The Digital-Alpha Recording System

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The digital-alpha waveform recorder, simply called “digital alpha,” is a specialized recording system (Figure 1) that has been customized to record optimally the exponentially increasing reaction history signal from a nuclear explosion. This technique uses a resistive voltage divider network to trigger a series of discriminators at pre-calibrated voltage levels. These discriminators provide the stop signal to time interval meters (TIMs)—which are precise digital clocks that share a common start signal in the digital alpha system. The output of the system is a set of voltage-time pairs that describe the input signal. Compared to other recording techniques, this system is easy to calibrate and use, and the data are recorded in a form that is easy to analyze. It has proved to be exceptionally stable when stored for over ten years and therefore may be easily maintained in a state of readiness in case of need.

Historically, the signal from a detector was recorded piecemeal by several Rossi oscilloscopes whose output is a Lissajous-like trace. One axis is driven by a stable time-reference oscillator; the other axis is driven by the signal from the alpha detector. The trace is recorded on film. Many Rossi oscilloscopes are needed to obtain a complete measurement, and a highly trained support staff is needed to operate and maintain them. The analysis of the data is time consuming and difficult—a great deal of effort is required to read the film and piece together the data. Nevertheless, this recording technique has been used on most nuclear tests and is the standard against which other systems must be judged. Much of the expertise in the use of Rossi oscilloscopes has been lost—or soon will be. Transient digitizers could, in principle, provide a modern replacement of these oscilloscopes. However, there are unresolved problems with digitizers because of their limited dynamic range and the lack of experience in using them to record reaction histories of nuclear events. Digital alpha is an automated, precisely calibrated system that is robust, is relatively easy to use, and produces data in a form that is easy to analyze and interpret.

The digital-alpha recording technique originated in the 1970s and was modernized in the late 1980s by the LANL high-speed electronics team and the electronics support group at EG&G (which is now Bechtel Nevada). Digital alpha was deployed on four nuclear tests—the results agreed to within about a percent with legacy systems. Although there is far less experience in operating this recording system than there is with oscilloscope-based techniques, digital alpha is intrinsically far simpler and will therefore more likely return data successfully with inexperienced operators than would a scope-based technique. Digital alpha should therefore be considered as a complement to, or replacement for, the usual reaction-history recording techniques. The system has been customized for reaction-history measurements by optimizing voltage-divider steps for the expected form of the signal. The system could be adapted to other fast-transient signals by customizing it in a similar manner—or by using it as is.

Figure 1. Archival photo of the “digital alpha” system used in experiments at the NTS.

The Signal

The reaction-history signals are related to the rate of production of neutrons in a nuclear device, as follows:

$$\frac{dn}{dt} = \alpha(t)n, \tag{1}$$

where n(t) is the density of free neutrons in the device, and α(t) is a multiplication rate, which depends on environmental variables such as the density of fissionable materials and therefore on time. We assume that our detector generates a current proportional to n(t) and that this current into a coaxial cable gives us the recorded voltage signal. It obeys the same equation as n(t), whereby

$$\frac{dV}{dt} = \alpha(t)V \tag{2}$$

An operationally useful form of Equation 2 is

$$\alpha(t) = \frac{1}{V}\frac{dV}{dt} = \frac{d\ln(V)}{dt} \tag{3}$$

Alpha is the time derivative of the natural logarithm of the signal. The measurement of α(t) is the reaction-history measurement. As long as α is positive, ln(V) (and therefore V) increase monotonically with time. The voltage signal of interest is easily determined by integrating Equation 3, as follows:

$$V(t) = V_0 e^{\int_{t_0}^{t} \alpha(\tau)d\tau} \tag{4}$$

The signal from a given alpha detector typically has a dynamic range of about four orders of magnitude; it emerges from the noise at about 0.5 V and ends when the cable breaks down at around 4 to 5 kV. The bandwidth of a cable is typically about 50 MHz, but the usable bandwidth can be stretched to about 300 MHz by equalizing networks that extend the flat part of the cable-response curve at the expense of signal amplitude. It takes a number of detectors, each with its own recording system, to cover the entire range of the reaction.

Digital-Alpha System Overview

As seen in Equation 3, a direct measurement of the logarithm of the voltage versus time is optimum for a measurement of alpha and has the additional advantage of extending the dynamic range of the system by logarithmic compression of the signal. It is hard to build logarithmic amplifiers of high precision, but it is straightforward to build voltage-divider networks with logarithmic increments and to calibrate these dividers precisely. This ladder network is customized for recording reaction histories.

The ladder in the network (Figure 2) is designed so that for each step the change in ln(V) is constant: $ln(V_{n+1}) - ln(V_n) = ln(V_{n+1})/V_n) = r$, or $V_{n+1}/V_n = e^{r}$. For the present network, r = 0.4. The voltage signal from each step of the ladder is fed into its own voltage discriminator, which generates a sharp timing pulse when its input threshold is reached. The TIMs have previously been given a common start signal and are stopped individually by the trigger pulse from their associated discriminator. Because the discriminator voltage threshold is calibrated, the stop times provide a time-versus-voltage measurement of the reaction-history curve. The TIMs can only be stopped once, so that the present system can only record the monotonically varying part of the signal (i.e., it works only as long as alpha does not change sign). The present TIMs have a time resolution of 50 ps, which is the time resolution of the system. The times are saved in nonvolatile memory so that the data can be read promptly—or later if that is more convenient. Both the timing circuits and the voltage divider network can be precisely calibrated using reference pulses; specialized calibration hardware has been built for this purpose. Alpha is simply expressed in terms of the data—it is the slope of the measured ln(V)-versus-time curve. The error analysis is straightforward, and the result is a well-characterized and well-calibrated reaction-history measurement.

Digital Alpha System Status

The present digital-alpha system was built during the last few years of underground nuclear testing and was under active development right up to the cessation of testing. It was then stored in pieces at Bechtel Nevada until about early 2002 when it was reassembled. Figure 3 compares a calibration of the ladder-discriminator network carried out in 1990 to a calibration of the same network carried out in 2003. The data are the ratios of voltages at adjacent positions in the ladder versus position in the ladder—both measured in powers of **e**. The ladder was built with 1% resistors. The large fluctuations around the design value reflect precision of the resistors. The repeatability of measurements of the ratio is about 0.2%, which is about the variation observed when the measurement is repeated after more than ten years. The system shows no apparent degredation in performance from storage over long periods.

Conclusion

The digital-alpha system is well suited to be held in readiness for a resumption of underground nuclear testing over time scales of decades. It is stable, robust, and relatively easy to use. It provides data in a form that is easy to analyze and characterize; it can therefore be used and understood even after the present generation of experienced test personnel is unavailable. The system is also well suited for the measurement of other fast-transient signals, either by customizing the ladder network to match the expected form of those signals or by using the system as is to take advantage of its logarithmic-compression capability. Applications of this system to experiments other than nuclear testing should be explored further.

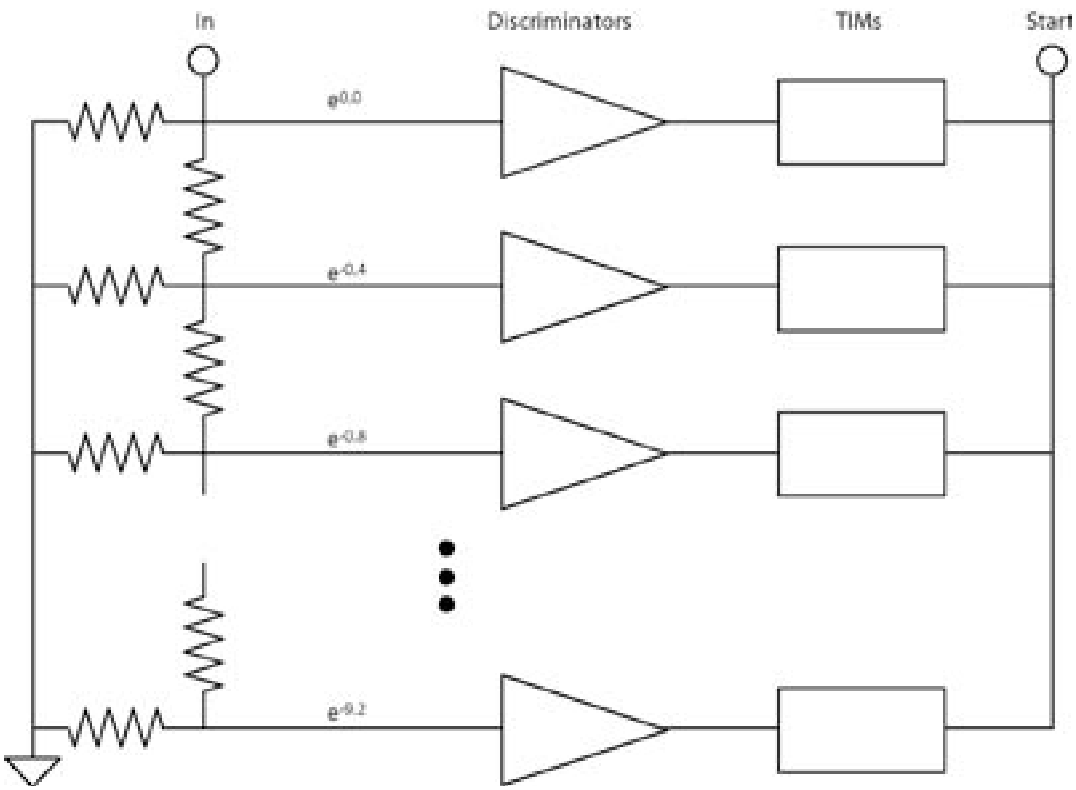

Figure 2. Schematic of the ladder-discriminator-TIM network. The TIMs are started with a common signal. They are individually stopped by the discriminators, which are triggered by the signals from the ladder. The attenuation factor at points in the network is indicated by numbers of the form e^{-x}.

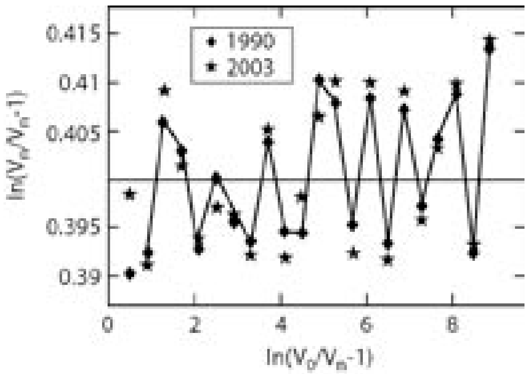

Figure 3. Calibration of the ladder-discriminator network in 1990 and 2003. The points represent the ratio of ln(V) values at adjacent steps along the ladder network. The position along the network is given by the natural logarithm of the attenuation factor. The network was stable over the time that it was stored.

Acknowledgment

The digital-alpha system was stored for twelve years at Bechtel Nevada; some of it was scattered over the NTS. Mike Carlisle (Bechtel Nevada) found all of the pieces of the system, including the system documentation and listings of the data-acquisition and control code. The system could not have been resurrected without his enthusiastic participation. Lyle Jensen and Kathy Breeding (Bechtel Nevada) made essential technical and archeological contributions. They represent much of the remaining expertise on the system hardware and software, respectively, and were invaluable participants in the early phases of this work. Eric Raby (P-21) showed remarkable skill and persistance in rewriting the ancient MSDOS and Windows data-acquisition and -control software to run under a modern operating system. P-21 consultant, Harvey Packard, was able to read the old computer backup tapes containing the design files for the calibration equipment so that these custom designs are not lost. This work was funded under the DOE Enhanced Test Readiness Program.

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